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A Detailed Study on the Equal Arrival Time Surface Effect in Gamma-Ray Burst Afterglows

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Abstract Due to the relativistic motion of gamma-ray burst remnant and its deceleration in the circumburst medium, the equal arrival time surfaces at any moment are not spherical, but should be distorted ellipsoids. This will leave some imprints in the afterglows. In this article, we study the effect of equal arrival time surfaces numerically under various conditions, i.e., for isotropic fireballs, collimated jets, density jump conditions, and energy injection events. For each condition, direct comparison between the two instances when the effect is and is not included, is presented. For isotropic fireballs and jets viewed on axis, the effect slightly hardens the spectra and postpones the peak time of afterglows, but does not change the shapes of the spectra and light curves significantly. In the cases when a density jump or an energy injection is involved, the effect smears the variability of the afterglows markedly.

Key words: gamma rays: bursts — relativity — shock waves — ISM: clouds

1 INTRODUCTION

Afterglow observations have made it clear that gamma-ray bursts (GRBs), both long and short, typically lie at cosmological distances (Costa et al. 1997; Frail et al. 1997; Galama et al. 1997; Vreeswijk et al. 1999; Hjorth et al. 2002; Villasenor et al. 2005; Fox et al. 2005), with the highest redshift recorded so far being $z \sim 6.3$ for GRB 050904 (Tagliaferri et al. 2005; Haislip et al. 2006; Price et al. 2006; Watson et al. 2006; Cusumano et al. 2006). Evidence is also accumulating, supporting the idea that long/soft GRBs may come from the collapse of massive stars, while short/hard GRBs come from the merger of two compact objects (Barthelmy et al. 2005). As the most violent bursts in the Universe since the Big Bang, GRBs and their afterglows can be satisfactorily understood in the framework of the relativistic fireball model, which postulates

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that the main burst emission should be due to internal shocks and the afterglow emission can be accounted for by external shocks (Mészáros & Rees 1992, 1997; Sari, Narayan, & Piran 1996; Vietri 1997; Wijers, Rees, & Mészáros 1997; Sari, Piran, & Narayan 1998; Dermer, Chiang, & Böttcher 1999; Su et al. 2006; and for recent reviews, see: van Paradijs, Kouveliotou, & Wijers 2000; Piran 2004; Zhang & Mészáros 2004).

GRBs are one of the most relativistic phenomena in our cosmos. The initial bulk Lorentz factor of GRB ejecta can be as high as 100 — 1000. Such an ultra-relativistic motion imposes two effects on the afterglows. First, the emission is strongly enhanced toward the direction of motion due to relativistic boosting. Second, photons emitted simultaneously from a spherical surface of the GRB remnant do not reach the observer at the same time. Photons at higher latitude will arrive later. In other words, at any lab-frame time, while the shape of the GRB remnant itself is spherical, the photons received by the observer actually do not come from a spherical surface, but from a distorted ellipsoid, i.e., the equal arrival time surface (Waxman 1997; Panaitescu & Mészáros 1998; Sari 1998; Granot, Piran, & Sari 1999; Gao & Huang 2006). Additionally, if angularly resolved by a telescope, the equal arrival time surface (EATS) would not be homogeneous in brightness, but would show a ring-like structure.

The exact analytical expressions for the geometric shape of EATS can be derived under some simplified assumptions in the ultra-relativistic stage, for example, in the cases of fully radiative and adiabatic regimes (Bianco & Ruffini 2005). But the EATS effect on the emission can be well incorporated in modeling of GRB afterglows only through numerical calculations. This has been done by a few authors (Panaitescu & Mészáros 1999; Moderski, Sikora, & Bulik 2000; Huang et al. 2000a, 2000b; Salmonson 2003; Kumar & Granot 2003; Granot 2005). However, a direct comparison between the two instances where the EATS influence is and is not included, which can reveal the effect more apparently, is still lacking. In this article, we intend to carry out the comparison. The structure of our paper is organized as follows. We describe our model in §2. Numerical results are then presented in §3 under various conditions, for example, for isotropic fireballs, jets, energy injections, and density variations in the circumburst medium. Finally, §4 is our conclusion and discussion.

2 MODEL DESCRIPTION

According to the standard fireball theory, afterglows are produced when the GRB ejecta, either isotropic or highly collimated, ploughs through the circumburst medium, producing a strong blastwave that accelerates the swept-up electrons. Synchrotron emission from these electrons is the dominant radiation mechanism that takes effect in the afterglow stage, although inverse Compton scattering may also play a role in some cases (Wei & Lu 2000; Sari & Esin 2001). The GRB ejecta is initially ultra-relativistic, but may become trans-relativistic in a few months (Huang et al. 1998), and enter the deep Newtonian phase in two or three years (Huang & Cheng 2003). Additionally, the blastwave is in the highly radiative regime in the initial few hours, but will be adiabatic thereafter.

A simple model that can realistically depict the overall evolution of GRB afterglows and which is also very convenient to solve numerically has been proposed by Huang et al. (Huang et al. 1999, 2000a, 2000b; Huang & Cheng 2003). We will use this model for the current study. Now we first describe the model briefly for completeness. In the description below, unless declared explicitly, physical quantities are all measured in the observer’s static lab frame.

The model is mainly characterized by a generic dynamical equation of (Huang et al. 1999),

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{\text{ej}} + \epsilon m + 2(1 - \epsilon)\gamma m}, \quad (1)$$

where γ is the bulk Lorentz factor of the shocked medium, m is the swept-up mass, M_{ej} is the initial mass of the GRB ejecta, and ϵ is the radiative efficiency. Equation (1) is applicable in both the ultra-relativistic and the non-relativistic phases (Huang et al. 1999). For collimated GRB ejecta, the lateral expansion is described realistically by (Huang et al. 2000a, 2000b),

$$\frac{d\theta}{dt} = \frac{c_s(\gamma + \sqrt{\gamma^2 - 1})}{R}, \quad (2)$$

where θ is the half-opening angle of the jet, R is the radius of the shock, and t is observer's time. c_s is the comoving sound speed, which is further given by

$$c_s^2 = \hat{\gamma}(\hat{\gamma} - 1)(\gamma - 1) \frac{1}{1 + \hat{\gamma}(\gamma - 1)} c^2, \quad (3)$$

with $\hat{\gamma} \approx (4\gamma + 1)/(3\gamma)$ being the adiabatic index.

To calculate synchrotron radiation from the shock-accelerated electrons, the electron distribution function is a key factor. Basically the electrons follow a power-law distribution according to their energies, with the power-law index p typically varying between 2 and 3. Here we adopt a refined function that takes into account the cooling effect (Dai, Huang, & Lu 1999; Huang & Cheng 2003). Note that our distribution function is applicable even in the deep Newtonian phase (Huang & Cheng 2003). As usual, we assume that the energy ratios of electrons and magnetic field with respect to protons are ξ_e and ξ_B respectively.

In order to include the EATS effect, the observed afterglow flux density at any given time t should be calculated by integrating over the EATS determined by

$$\int \frac{1 - \beta \cos \Theta}{\beta c} dR \equiv t, \quad (4)$$

within the ejecta boundaries (Moderski et al. 2000), where $\beta = \sqrt{\gamma^2 - 1}/\gamma$ and Θ is the latitude angle on the EATS. In our model, it is also very convenient to remove the consideration on EATS, so that we can clearly see how the EATS takes effect in GRB afterglows. For details on how to calculate the dynamics and the radiation process, readers may refer to Huang et al.'s original articles (Huang et al. 1999, 2000a, 2000b; Huang & Cheng 2003).

3 NUMERICAL RESULTS

In this section, we use our model to investigate the EATS effect in GRB afterglows under various conditions. In each condition, we will directly compare the two instances where the EATS influence is and is not included. For convenience, we first define a set of “standard” parameters that will be generally used in our calculations: $\xi_e = 0.1$, $\xi_B = 0.001$, $p = 2.5$, the isotropic equivalent energy of the GRB ejecta $E_{0,\text{iso}} = 10^{53}$ ergs, the initial Lorentz factor $\gamma_0 = 300$, the number density of the circumburst medium $n = 1 \text{ cm}^{-3}$, and the luminosity distance of the GRB $D_L = 1 \text{ Gpc}$. For jets, we take the initial half-opening angle as $\theta_0 = 0.1$. These parameter values are quite typical in GRB afterglows.

3.1 Isotropic Fireballs

In Figure 1, we illustrate the evolution of the afterglow spectrum for an isotropic fireball with “standard” parameters. The solid lines correspond to the instance when the EATS effect is included, while the dashed lines correspond to the case when the EATS effect is omitted. A few interesting features can be clearly seen from this figure. First, the spectrum at any particular moment can be divided into three segments. Taking the spectrum at $t = 10^5 \text{ s}$ as an example,

the three segments are approximately $S_\nu \propto \nu^{0.34}, \nu^{-0.76}, \nu^{-1.27}$ respectively. They are in good agreement with theoretical expectations, i.e., $S_\nu \propto \nu^{1/3}, \nu^{(1-p)/2}, \nu^{-p/2}$ (Sari, Piran, & Narayan 1998). Note that the EATS does not change the slope of each segment. Secondly, the peak flux density ($S_{\nu, \text{max}}$) does not evolve significantly with time. This is true irrespective of the EATS consideration. However, the inclusion of the EATS does reduce $S_{\nu, \text{max}}$ by a factor of ~ 2 . Thirdly, the EATS effect makes the spectrum slightly harder. As a result, the peak frequency ν_{max} (corresponding to $S_{\nu, \text{max}}$) is slightly higher, and the emission below ν_{max} is reduced while that above ν_{max} is enhanced. This effect is easy to understand. On an EATS, the material at high latitude actually corresponds to an earlier stage of the ejecta shell, which has a larger Lorentz factor and naturally emits harder photons. Additionally, electrons enclosed in an EATS is fewer in number than those in the corresponding sphere. This is the reason of the reduction of $S_{\nu, \text{max}}$ as mentioned above.

Finally, we also note that the EATS effect is less significant at very high frequency. For example, there is little difference between the solid line and its corresponding dashed line when $\nu \geq 10^{17}$ Hz. This can also be easily understood. High energy photons are mostly emitted by high speed materials, which mainly reside at the top point of the EATS and whose emission is restricted within a small solid angle due to relativistic beaming effect. In other words, high energy photons are emitted from a small portion of the EATS which is at the top point and which differs from a sphere marginally.

Figure 2 shows the EATS effect on the R-band afterglow light curve. An obvious feature is that the EATS effect postpones the peak time (t_{peak}) of optical afterglow by a factor of ~ 2 . Also, before the peak time, the EATS effect makes the afterglow dimmer, but after the peak time, it makes the afterglow slightly brighter. However, the EATS effect does not alter the slopes of the light curve, either before or after the peak time. Figure 3 illustrates the EATS effect on X-ray afterglows. While the basic features of Figure 3 are generally similar to those of Figure 2, an obvious difference is that the dimming and brightening of X-ray emission before and after the peak time due to the EATS effect are much shallower. It is consistent with the spectral characteristics revealed in Figure 1.

3.2 Jets

The EATS effect on the optical afterglow of jets are illustrated in Figure 4. Generally speaking, the role played by the EATS on jets is quite similar to that on isotropic fireballs, i.e., postponing the peak time, reducing the brightness before t_{peak} , and enhancing it after t_{peak} .

Figure 5 shows the afterglow light curves when the observer is off-axis. An obvious feature can be immediately noted in this figure that the dashed line is much higher above the solid line when $t < t_{\text{peak}}$. This behavior is not completely unexpected. As we know, when an observer is off-axis, the observed flux will be very low due to relativistic beaming. When EATS is taken into account, high latitude photons actually come from material with larger Lorentz factors, which means the beaming effect is more serious. The effect is especially notable at early stages ($t < t_{\text{peak}}$), when the decrease of the Lorentz factor of the jet is extremely rapid.

3.3 Density Jump Cases

When the GRB ejecta encounters a sudden density increase in the circumburst medium, a rebrightening of the afterglow will be observed (Lazzati et al. 2002; Nakar & Piran 2003; Dai & Wu 2003; Tam et al. 2005). It would be of interest to investigate how the EATS takes effect when such a brightness variation is involved. Here we assume that the number density of the circumburst medium jumps suddenly from 1 cm^{-3} to 100 cm^{-3} at the observer's time 2×10^4

s (corresponding to a radius of $R_J \sim 4.5 \times 10^{17}$ cm). The numerical results are presented in Figures 6 — 7.

Figure 6 shows a few surfaces of equal arrival times, comparing them directly with the spherical geometry of the jet. At early stages, when the jet is still highly ultra-relativistic, the EATSes are very flat and deviate from spherical surfaces seriously. However, it is interesting to note that the foreland of the EATS becomes obtuse when $R > R_J$. This is because the jet decelerates rapidly after the density jump, making the relativistic effect less significant. At the time of 10^6 s, when the Lorentz factor of the jet is $\gamma \sim 1.2$, the EATS no longer deviates from the sphere so markedly. In our calculations, when the blastwave reaches the density jump radius, its Lorentz factor is $\gamma \approx 9$. Thus the EATS will completely pass through the density jump surface at a time of $R_J/\gamma^2 c \sim 1.9 \times 10^5$ s. This can also be clearly seen in Figure 6.

Figure 7 shows the R-band afterglow light curves. The dashed line in Figure 7a corresponds to the instance when the EATS effect is not considered. We see that a sharp rebrightening does appear at the density jump moment. However, the flux density decreases steeply soon after the density jump. This is mainly due to the rapid deceleration of the blastwave in a much denser environment. When the EATS effect is included in our calculation, the rapid variation is largely smeared and the light curve (the solid line) becomes very different. First, the rapid decline of the brightness seen at $t > 2 \times 10^4$ s in the dashed line is now postponed to $\sim 2 \times 10^5$ s. This is easy to understand. We know that the EATS is not homogeneous in brightness, but shows a ring-like structure, which means emission from the high latitude portion plays the dominant role in afterglows (Waxman 1997; Sari 1998; Panaitescu & Mészáros 1998). At any time $2 \times 10^4 \text{ s} < t < 2 \times 10^5$ s, although the central portion of the EATS is in the high density region so that the emission is very weak, the high latitude portion of the EATS, which dominates the afterglow emission, is still in the low density region (see Figure 6) and the emissivity remains at a high level. So, the afterglow flux will not be affected too much by the density increase during this period. However, when $t \geq 2 \times 10^5$ s, the EATS passes through the density jump radius completely and the emissivity of the whole EATS becomes very low. The afterglow then naturally shows a steep decline. Second, the pulse-like rebrightening structure at exactly 2×10^4 s in the dashed line also leaves its fingerprint in the solid line. As a result, we can observe a shallow but clear rebrightening in the solid light curve beginning at the time of the density jump.

In reality, the density jump is usually due to the existence of a dense molecular cloud. Since molecular clouds can be magnetized, it is possible that the ξ_B parameter may be correspondingly much larger after the density jump in some cases. In Figure 7b, we assume that at the density jump radius, the ξ_B parameter increases by a factor of 50 at the same time. This induces a prominent pulse-like structure in the dashed light curve when the EATS effect is expelled. When the EATS effect is included, the rebrightening is still very salient. This mechanism may give an explanation to the marked rebrightenings observed in some GRB afterglows.

3.4 Energy Injection Cases

Evidence for prolonged activities of the central engines of GRBs has been found in a few events (Dai & Lu 2001; Zhang & Mészáros 2002; Björnsson, Gudmundsson, & Johannesson 2004; Fan et al. 2004; Burrows et al. 2005; King et al. 2005; Watson et al. 2006). Here we assume that the kinetic energy of the GRB remnant increases instantly by a factor three at $t = 2 \times 10^4$ s due to a sudden energy injection. The corresponding optical light curves are shown in Figure 8. Again we see that the effect of the EATS is to smoothen the light curve variability.

4 CONCLUSION AND DISCUSSION

In this article we study the EATS effect on GRB afterglows through numerical calculations. Generally speaking, for isotropic fireballs and jets viewed on the axis, the inclusion of the EATS consideration does not change the shapes of afterglow spectra and light curves. However, it does slightly harden the spectra, and postpones the peak time of the light curves. Additionally, the EATS effect tends to decrease the flux density when $t < t_{\text{peak}}$, but increase the brightness when $t > t_{\text{peak}}$. In X-ray bands, the EATS effect is weaker than that at optical frequencies.

When the GRB ejecta encounters a sudden density jump in the circumburst medium, the emissivity of the blastwave first rises rapidly, but it will then decrease steeply to a much lower level due to the rapid deceleration of the shock in a denser environment. In this case, the EATS effect changes the afterglow light curve significantly, shaping the originally pulse-like structure into a much weaker but much longer rebrightening. In case of energy injection, the EATS has a similar effect, i.e., smoothing the variability of the light curve.

Our studies on the EATS effect have important implications on observations. A good example is GRB 030329, for which a marked rebrightening was observed at $t \sim 1.6$ d in the optical afterglow (Lipkin et al. 2004). Huang, Cheng and Gao (2006) have reexamined this event numerically in light of three models, i.e., the density-jump model, the two-component jet model, and the energy-injection model. EATS effect was considered in their calculations. They found that the energy-injection model is the most preferred choice for the rebrightening. However, even in their best fit to the optical afterglow by engaging the energy-injection model, the theoretical rebrightening is still not rapid enough as compared with observations, due to the EATS effect. This hints that we still need to seek other physical process for the rebrightening.

In the density jump case considered in our current study, there is a possibility that the portion of magnetic field energy (i.e., the ξ_B parameter) may also increase at the jump radius. This may happen when the density jump is caused by a magnetized molecular cloud. In this case, a prominent rebrightening is expected even if the EATS effect is taken into account. It is characterized by a rapid increase at the beginning and a steep decrease after the jump front completely passes through the EATS. This mechanism may give a natural explanation to the rebrightenings observed in some GRBs. For GRB 030329, it is quite probable that the ξ_B parameter might also change at the energy-injection moment, which may help to fasten the rebrightening. This possibility needs further study in the future.

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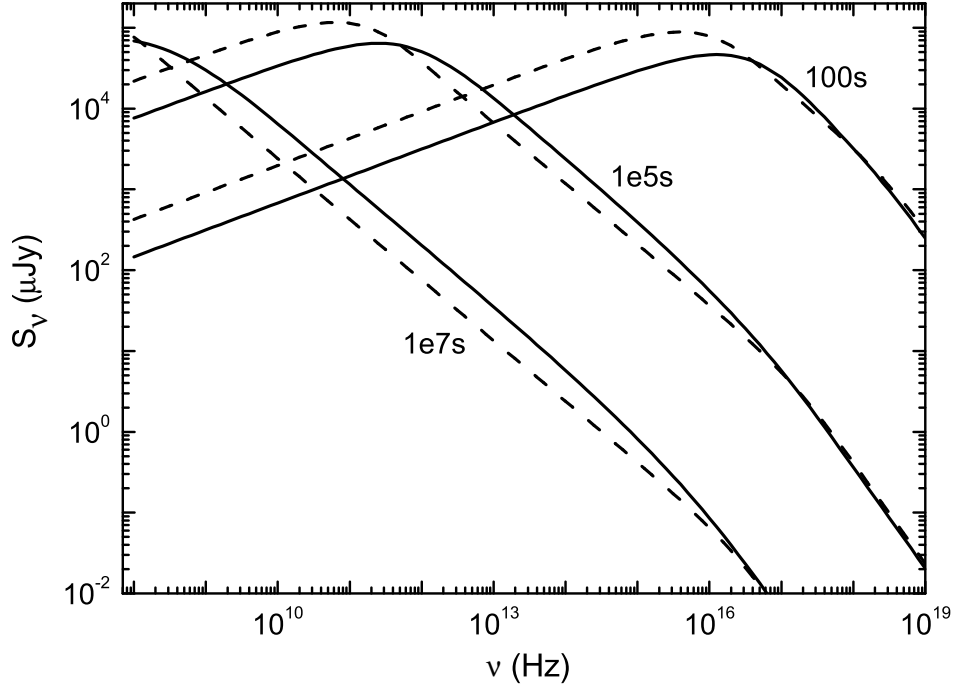


Fig. 1 Spectrum evolution of an isotropic fireball with “standard” parameters. The solid lines are drawn with the EATS effect included. As a comparison, the dashed lines do not incorporate the EATS effect. The number near each pair of curves indicates the time at which the spectra are sampled.

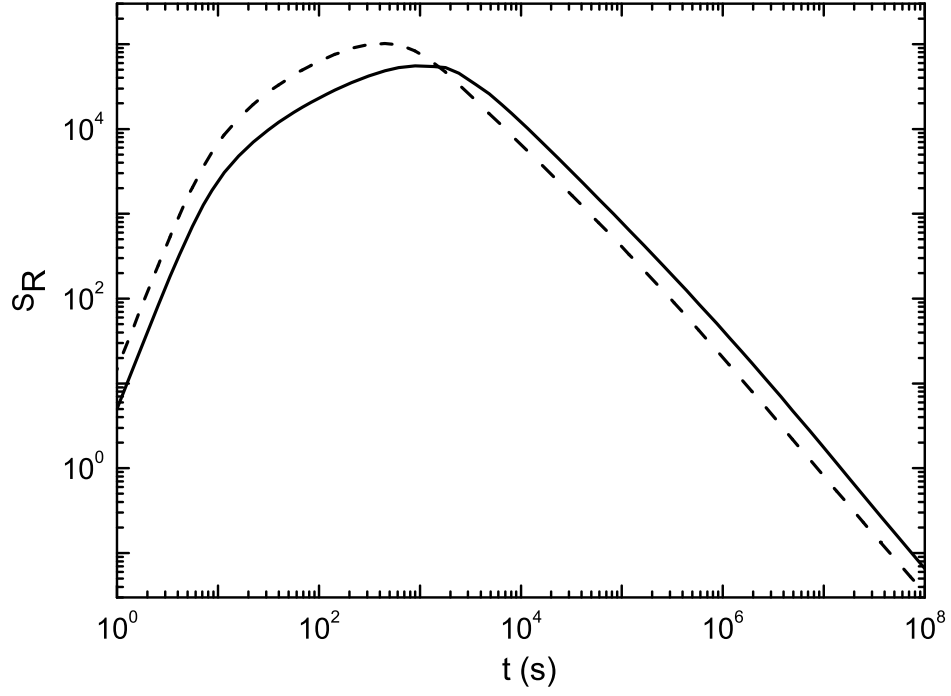


Fig. 2 R-band afterglow light curves of an isotropic fireball. Line styles and parameters are the same as in Figure 1.

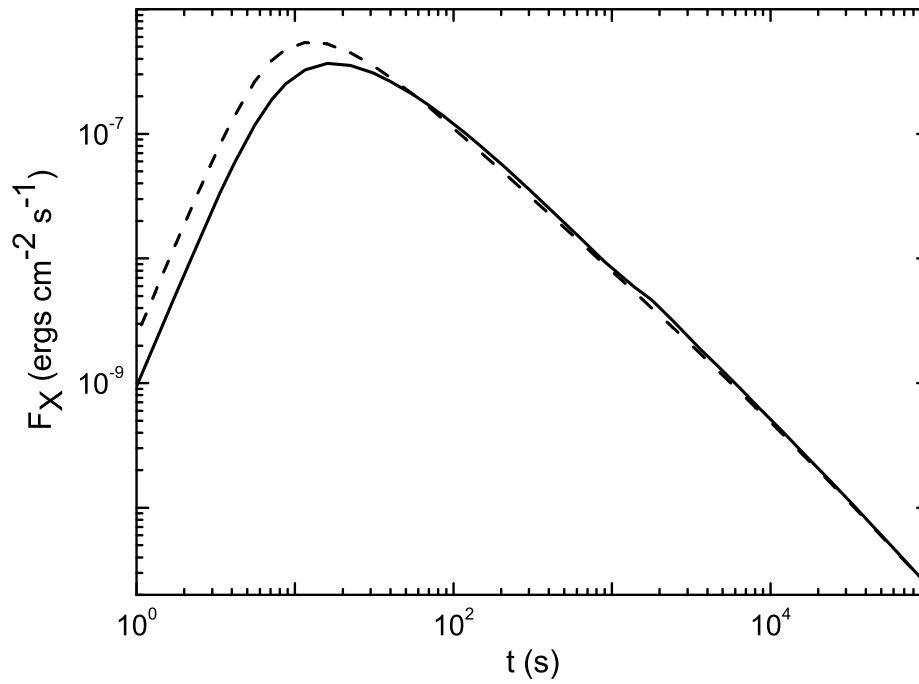


Fig. 3 0.1 — 10 keV X-ray afterglow light curves of an isotropic fireball. Line styles and parameters are the same as in Figure 1.

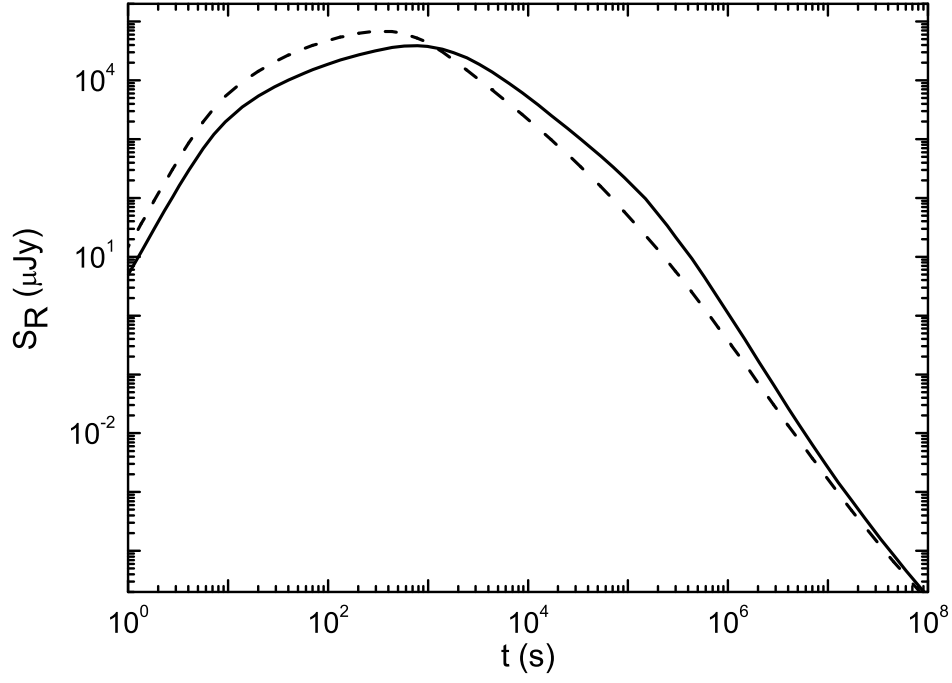


Fig. 4 R-band afterglow light curves of a jet with “standard” parameters. The solid line is drawn with the EATS effect considered, while the dashed line is drawn with the effect excluded.

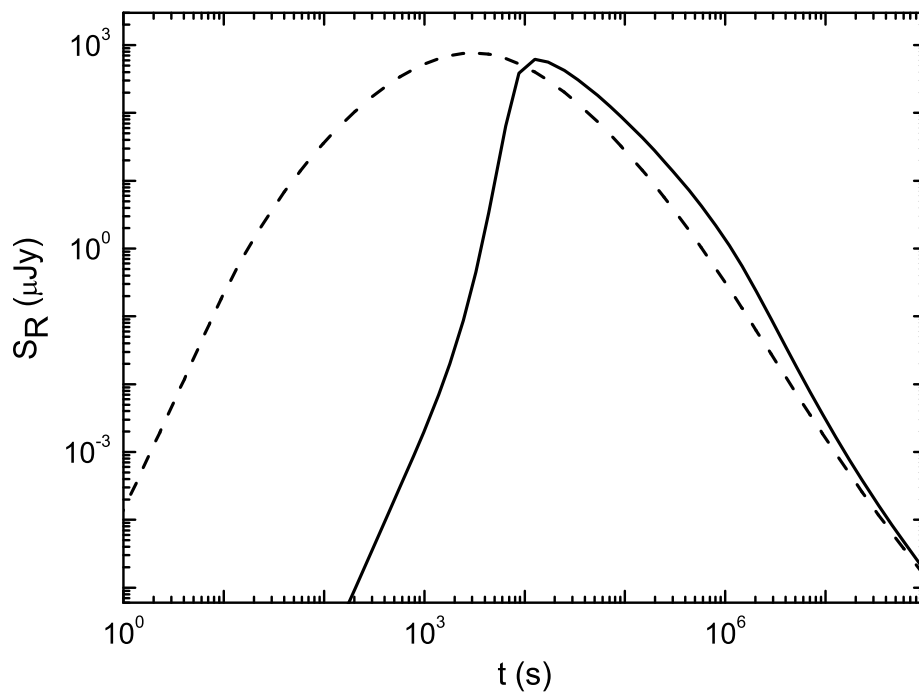


Fig. 5 R-band afterglow light curves of a jet with “standard” parameters, but viewed at an angle of 0.17. Line styles are the same as in Figure 4.

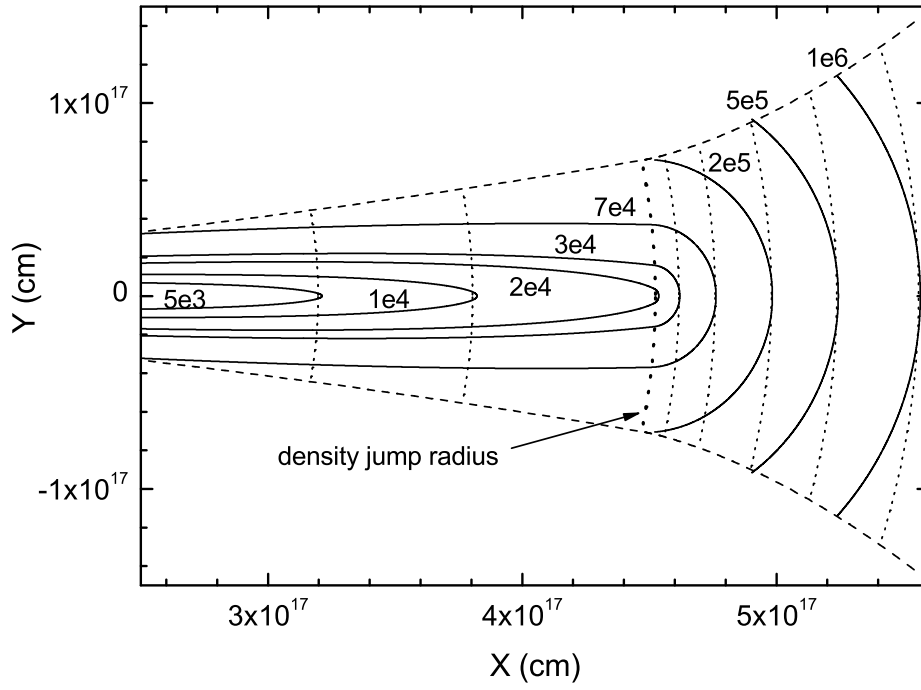


Fig. 6 Exemplar surfaces of equal arrival times for a “standard” jet encountering a density jump at $t = 2 \times 10^4$ s. The amplitude of the density jump is 100 times. X-axis is the direction of motion of the jet, and Y-axis is the lateral direction. The solid lines illustrate the equal arrival time surfaces, with the time marked in units of s. The dotted lines show the corresponding spherical surfaces. The dashed lines are jet boundaries.

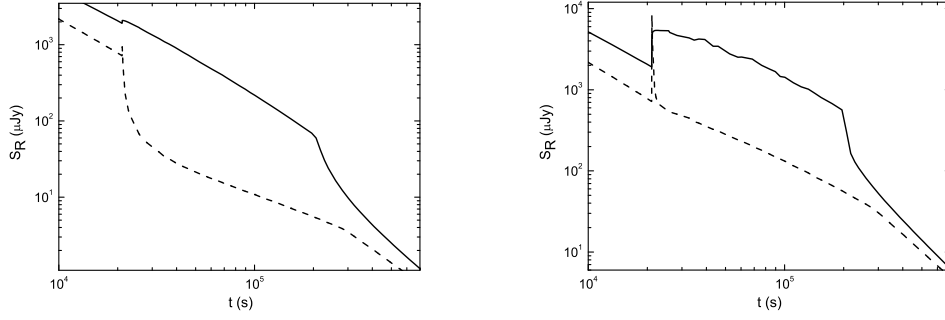


Fig. 7 (a) R-band afterglow light curves of a jet encountering a density jump at $t = 2 \times 10^4$ s. The amplitude of the density jump is 100 times. Other parameters involved are the same as in Figure 4. The solid line and the dashed line correspond to the instances when the EATS effect is and is not included, respectively. (b) Same as (a), except that the ξ_B parameter increases by a factor of 50 simultaneously at the jump radius.

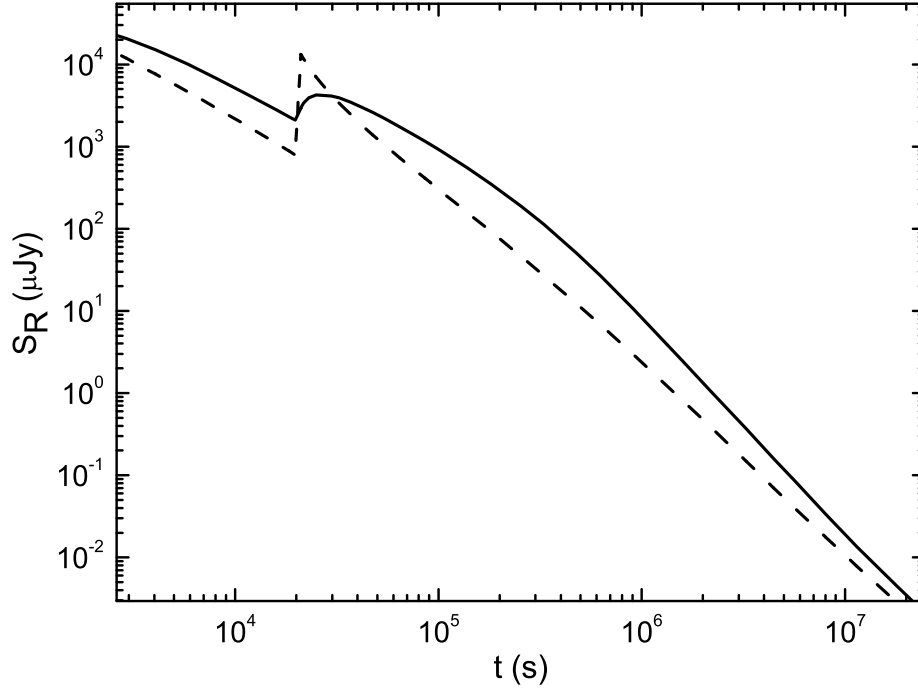


Fig. 8 R-band afterglow light curves of a “standard” jet in case of an energy injection occurring at 2×10^4 s. The energy supply is assumed to be completed instantly, which increases the total kinetic energy of the GRB remnant by a factor of 3. The solid line is drawn by including the EATS effect, and the dashed line is drawn with the effect excluded.